ONR/URI FINAL TECHNICAL REPORT

Principal Investigators:
Victor R. Lesser
Paul Cohen
Wendy Lehnert

University of Massachusetts, Amherst, MA
(413) 545-1322
Lesser@cs.umass.edu

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Program objectives:

The primary objective of our research program was the development and integration of enabling technologies for the development of distributed decision support systems. This involved four major research areas: Knowledge Acquisition and Learning, Sophisticated Control, Situation Assessment and Accessing Large Memories. Due to significant budget reductions from the initial proposed levels, the proposed integration of these different research areas was removed as an objective, the research area of Learning and Accessing Large Memories was dropped as a major focus of the research program, and the work on Knowledge Acquisition was limited to semantic analysis of text documents.

URI has also provided the infrastructure to allow us to build a environment in terms of computing and support staff to perform AI research that has a significant emphasis on large system building and extensive empirical evaluation of research. As a result of URI funding, University of Massachusetts has been able to build up an AI research program that is considered one of the top programs in the world. Based on current research funding, we have the fourth largest program in the country. During or right after the termination of this grant, three of the principal researchers on this grant (Wendy Lehnert, Victor Lesser and Edwina Rissland) were made fellows of the AAAI, and two other researchers who benefited from the infrastructure provided by this grant (Robin Popplestone and Edward Riseman) were also made fellows.

Another benefit of the URI has been its ability to nurture high-risk research in its infancy that would not normally get funded through usual channels--explicitly, the work of Paul Cohen on AI methodologies and Wendy Lehnert on

semantically-oriented sentence analysis. Both of these research efforts are now being recognized as important contributions to the field.

Finally, URI funded post-doctoral positions for two of our Ph.D. students, Kevin Ashley and Edmund Durfee, allowing them to further expand their thesis research before taking academic positions. It is our feeling that this extra time allowed their Ph.D. research to mature significantly. Both of these students subsequently received Presidential Young Investigator Awards.

The new research areas that have been stimulated by URI include:

- The development of a suite of experimental tools that will assist knowledge engineers as they evaluate and improve the design of AI planning systems.

- Techniques for monitoring of agents working with limited attentional resources under time pressure and its use in plan steering.

- Using Failure Recovery Analysis in iterative design of agents and in the design of large software systems. FRA helps the agent designer find and fix those aspects of the agent design that are not suitable to the task.

- The integration of statistical information retrieval techniques and semantically-oriented sentence analysis for intelligent access to large text data bases.

- The development of generic frameworks for the implementation of coordination and negotiation strategies for distributed planning, scheduling and resource allocation applications.

- Techniques for adaptive signal processing (signal reprocessing) based on a bi-directional interaction between the signal processing subsystem and signal understanding subsystem.

- The development of mixed paradigm systems, including one based on a blackboard architecture and Cased-Based Reasoning.

<u>Accomplishments, organized by objective.</u>

Knowledge Acquisition - Natural Language Text Analysis

The major accomplishment in this area was the demonstration of a robust language analysis at MUC-3 (see Lehnert et al. papers). This system outperformed all other systems in the evaluation. This represents a breakthrough result for the management of complex syntax within a semantically-oriented sentence analyzer.

In the work on natural language processing, we completed an important performance evaluation process. We were one of fifteen research sites that participated in MUC-3, a DARPA-sponsored evaluation of sophisticated text analyzers operating on unconstrained news articles. Each system was required to extract detailed information about specific terrorist activities described in wire service stories, newspaper articles, interview transcripts, terrorist communiques, and other text sources. The UMass system was based on the CIRCUS sentence analyzer, and incorporated multiple architectures to enable selective concept extraction. In the final MUC-3 evaluation, UMass posted the highest recall score of all participating systems, as well as the highest combined scores for recall and precision.

On a theoretical level, our MUC-3 system was notable for two important innovations in text analysis. First, a powerful formalism for handling complex sentence structures within a semantically-oriented parser was put to the test with positive results. We have determined that 75% of the texts from the MUC-3 development corpus contained multiple clauses. Any system not capable of handling complex syntax would therefore experience severe difficulties in this evaluation. Given the overall performance of our system, we have established that a semantically-oriented parser can compete with more syntactically oriented systems very effectively. Second, we also incorporated a case-based reasoning component in our MUC-3 system for managing discourse analysis. This component operated in conjunction with a rule-based discourse analyzer, but nevertheless provided us with a level of performance that could not be duplicated with the rule base alone. This signifies a first attempt at handling discourse analysis with CBR technologies, and it appears to be a very promising direction for future research.

Historically speaking, it has been very difficult to obtain empirical evaluations for natural language processing technologies. Researchers routinely publish claims and speculative comparisons, but data to support these claims is typically unavailable or difficult to assess. The MUC-3 performance evaluation provided the NLP community with a remarkable opportunity to attempt an empirically-based evaluation. UMass was one of three university sites and 12 industry sites that completed the evaluation. Roughly one year of preparation went into this undertaking.

With our strong showing in the final evaluation, we have established that selective concept extraction is a highly viable strategy for detailed information extraction from full text. Our approach assumes only minimal dictionary coverage (6,000 words as opposed to 60,000 in at least one other system), and is also notable for achieving high performance with minimal syntactic analysis. Our system produces no syntactic parse trees for sentences or fragments of sentences, operating instead on a small set of buffers designed to capture only localized syntactic contructs. Semantically-oriented sentence analyzers are frequently criticized in the literature as ineffective in the face of realistically long and

complex sentences. Our MUC-3 evaluation shows that semantically-oriented sentence analysis is indeed a viable approach, at least as far as goal-oriented information extraction is concerned.

Remarkably, MUC-3 has taught us that sentence analysis may no longer be the primary stumbling block in the way of sophisticated text analysis. We have not been able to analyze our performance with respect to sentence analysis per se, but we suspect that more difficult problems occur at the level of discourse analysis, where information across multiple sentences must be collected and merged, or distinguished and pulled apart. Given this scenario, our success with a case-based reasoner for handling discourse analysis is extremely exciting, because the CBR component holds a number of advantages over its rule-based counterparts. Whereas a rule base for discourse analysis will be heavily domain-dependent, only minor modifications are needed to port a CBR discourse component from one text domain to another. In addition, all rule-based systems are difficult to scale up beyond some threshold of system complexity. But a CBR component can scale up very readily since the extraction of a case base can be fully automated (at least for our system), and thereby reconstructed to cover a larger text corpus as needed without any additional knowledge engineering. We expect a rich vein of research will now emerge with respect to text analysis and case-based reasoning.

Because DARPA was not able to fully support all the sites participating in MUC-3, we would not have been able to participate ourselves without the support available to us through URI. MUC-3 proved to be an extremely stimulating and positive experience for our natural language processing group, and we are now eager to pursue a variety of new research directions that became apparent as a result of our MUC-3 involvement.

Sophisticated Control - Real-Time and Distributed Coordination

There were four major accomplishments in this area. The first was the development and experimental validation of a new paradigm called Approximate Processing, for implementing real-time AI systems. This work presents an important alternative approach to the any-time algorithms approach to real-time AI.

We have made important progress towards both completing and generalizing real-time research started in the early stages of this grant. After a five-year research effort involving numerous intermediate steps, we have now fully implemented a real-time blackboard architecture for approximate processing. This architecture trades off precision, completeness and certainty of the solution against the time to generate a solution by having a set of different methods that can be applied in situation-specific contexts. This architecture includes approximate representations for intermediate stages of processing, a parameterized low-level control loop that permits the system to be dynamically

configured for specific approximation strategies, a high-level control planning architecture that permits the system to explicitly represent and reason about its goals and appropriate approximations, and a design-to-time scheduling algorithm and execution subsystem that schedules tasks based on hard deadlines and alerts the high-level controller to unexpected changes in task characteristics. This new real-time architecture has been implemented in an extended version of the Distributed Vehicle Monitoring Testbed (DVMT).
[The Distributed Vehicle Monitoring Testbed (DVMT) has been extended to integrate approximate processing techniques for
real-time performance. A new control architecture has been implemented for approximate processing that responds to time constraints on the interpretation task by combining approximate and precise data. This combination requires new ways of handling the uncertainty introduced by combining imprecise and precise data. The belief representation used in the DVMT has been enhanced to distinguish uncertainty in the domain, and in precise data, from that introduced by the use of approximate data. In addition, a framework for representing and applying different classes of approximate knowledge has been developed.]

The second major accomplishment in this area was the design and implementation of a new agent architecture to support adaptable planning and scheduling. It presents methods for reasoning about real-time constraints, and techniques for plan monitoring and failure recovery.
Ongoing work with the Phoenix system has led to formalizations for describing interactions between agents and their environments along with extensive empirical experiments for the purpose of evaluating those formal models. Because Phoenix attempts to model effective problem solving behavior in complex, real-time environments, the issue of what constitutes an acceptable solution or near-optimal solution is both challenging and crucial to meaningful system evaluations. An empirical interface to Phoenix has therefore been designed to facilitate interactive experiments and data analysis covering large numbers of simulations.
?[We have also applied techniques originally developed in Phoenix, for real-time monitoring of progress and for steering plans developed, to the transportation domain. This technique, called {em envelopes}, represents the progress of plans in such a way that failure can be anticipated before it occurs, allowing the system to "steer" itself around potential problems. For the transportation problem, we model nodes in a transportation network and build demons that use envelope-like structures that recognize pathological states before they arise. Once a pathological state is predicted, the system will present a visualization of the evolving pathology to an operator, along with suggestions about how to steer around it. This approach will form the basis for a plan steering architecture, both for human-computer systems as in the transportation problem and for autonomous agents such as those in Phoenix.]

The third major accomplishment was the development of a new AI methodology emphasizing the analysis of the behavior of AI programs, using simulation to expose programs to the myriad of interacting problems found in real-world environments, and analyzing program performance using statistical methods from the behavioral sciences. This represents one of the first efforts to put the development of complex AI systems on a sound methodological basis.

During 1990 we developed the Modeling, Analysis and Design (MAD) methodology that we believe bridges the gulf between theoretical and systems-oriented AI research. This work grew in part out of a survey of papers submitted to AAAI 90 and gave impetus to a growing methodological debate. With sponsorship from NSF and DARPA, we held a workshop in June of 1991 to provide a forum for this debate and propose a common set of goals for improving AI methodology. Proceedings of the workshop and the participants' recommendations are being prepared for publication.

We have worked to apply our proposed MAD methodology within our own research and to develop the skills in our graduate students needed to conduct MAD research. We began a modeling summer school for graduate students. The curriculum was designed to teach research skills, including modeling complex systems and agent architectures, designing experiments to test the behavior of agents, and using statistical analysis techniques on experiment results. Phoenix is the "laboratory" for this work, providing a ready-made environment and agents designed to operate there. The three main goals of this summer's effort were to acquaint us with MAD in practice, to develop a complete model of Phoenix, and to lay the groundwork for a curriculum in *agentology*—the principled design of autonomous agents for complex environments.

The primary objective of our work with IGOR is to concentrate on understanding and automating the expert human process of incrementally building models from both experimental and non-experimental data. As such, this work represents the development of an enabling technology for principled Artificial Intelligence research using the MAD methodology. A computer program called IGOR is currently being designed and developed to function as a model-builder's intelligent assistant. The basic approach of IGOR is to integrate the complementary strategies of exploratory and confirmatory data analysis in a knowledge-based decision aid.

IGOR is being designed using the blackboard paradigm, where the shared blackboard data structure holds elements of the developing model, and the individual knowledge sources operate on those elements to create terms, hypothesize relationships, and perform statistical tests via library calls to the Common Lisp Analytical Statistics Package (CLASP), developed under URI in 1990. The long-term objectives for IGOR include fully automated model-building and discovery mechanisms driven by an opportunistic control strategy. We expect to develop the automated strategies from our experience with the system

as a manual analysis decision aid, letting human analysts provide the initial reasoning control strategy.

Many methods and algorithms have been developed for data analysis and model-building problems, including some parametric and non-parametric statistical techniques, automated discovery approaches from machine learning research, and attempts to develop purely data-driven methods for inferring causal structure. In developing IGOR we will consider methods of two primary types. First, there are exploratory methods, which are data-driven procedures for discovering patterns. The exploratory methods often emphasize the use of graphical displays, relying on human visual skills for pattern recognition. Since IGOR is being developed first as a model-builder's decision aid, these visualization techniques are particularly important. Second, there are confirmatory methods, which are goal- or theory-driven methods for answering specific questions, such as the likelihood that a particular observed pattern could have arisen by chance alone.

The fourth major accomplishment in this area was the development of a unified approach to distributed coordination, called Partial Global Planning. It represents a major new paradigm. A presidential young investigator award was given to Ed Durfee based on this research.
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Real-Time Control

The major developments this year in real-time control have been to introduce into a real-time blackboard architecture the ability to: divide the problem up into tasks; divide tasks up into subtasks that have distinct earliest start times; control the execution of each task separately so that different tasks (including different instances of the same kind of task) can use different approximations; estimate the time and solution quality for a task given a particular problem-solving method; monitor problem solving to notice the arrival of new tasks and notice unexpected behavior in existing tasks. Our real-time blackboard architecture implementation has two main components: a controller that decides which tasks to perform, what problem-solving methods to use for those tasks and when each task should be worked on; and an execution subsystem that micro-schedules the execution of steps of tasks and ensures that tasks perform as predicted.

Situation Assessment -- Interpretation and Case-Based Reasoning

One major accomplishment in this area was the extension of Case-Based Reasoning (CBR) techniques to incorporate precedence-based reasoning and traditional rule-based systems. This work significantly extends the domains in which CBR can be applied. A presidential young investigator award was given to Kevin Ashley based on the precedence-based reasoning aspects of this research.

A new project was begun to investigate the effectiveness of using inductive learning techniques in a case-based reasoning (CBR) system. CBR systems make mistakes for one of three reasons: the case base lacks a case, the wrong case was retrieved, or the retrieved case was not adapted properly to the current situation. This project focused on using inductive learning to reduce or eliminate errors in a CBR system's retrieval and adaptation mechanisms. Preliminary results from the domain of OTHELLO suggested that the addition of inductive learning yields both a performance improvement and a smaller case base.

Another major accomplishment in this area was the development of a new blackboard-based architecture for building complex signal understanding systems. It solves in an elegant and general way many of the evidential and control limitations present in the original Hearsay-II architecture.

We made major progress in the development of a new paradigm to integrate signal processing and signal understanding. We call this approach IPUS (Integrated Processing and Understanding of Signals). This paradigm permits sophisticated interaction between the theory-based problem solving at the signal processing levels and heuristic problem solving at the interpretation levels. The need for such a paradigm and its realization in an architecture arises in signal understanding domains with complicated interacting signals under variable signal-to-noise ratios. An implementation of this paradigm for use in an abstracted version of a sound understanding task has been completed. This system indicates that the basic functionality of IPUS can be implemented in a computationally efficient way, and is effective.

The IPUS architecture is built on top of the RESUN framework that was developed and enhanced under URI funding. The RESUN framework has two key components: an evidential representation that includes explicit, symbolic encodings of the sources of uncertainty (SOUs) in the evidence for hypotheses and a script-based, incremental control planner. Interpretation is viewed as an incremental process of gathering evidence to resolve particular sources of uncertainty.

In traditional signal understanding systems, the front-end signal processing is usually fixed for all input signals, and input signals are not reprocessed on the basis of the dynamics of the higher-level problem solving. Thus, the interaction between the interpretation problem solving and the signal processing is limited to a simple sequential scheme in which the former accepts the latter's output data. In contrast, we have developed a paradigm (IPUS) and implemented it in an architecture to achieve such interactions in a more general way, with an emphasis on utilizing the sophisticated signal processing theories that underlie many signal processing tasks in order to structure the cooperation between signal processing and signal understanding. An iterative technique for converging to the appropriate control parameter values is at the heart of the IPUS architecture. The technique begins by using the best available guess for the

control parameter values (in the worst case, the system resorts to arbitrary control parameter values). The input signal is then processed using the chosen control parameter values. The output is then analyzed through a discrepancy detection mechanism that indicates the presence of distorted output data. A diagnosis is then performed to obtain an "inverse" mapping from the detected discrepancies to distortion hypotheses. This diagnosis process utilizes the formal theory that underlies the signal processing carried out by the signal understanding system. The availability of such a formal theory is a major criterion for determining the IPUS architecture's applicability to any particular problem domain. A signal reprocessing planning phase then proposes a search plan for finding a new set of values for the control parameters of the signal processing with the aim of eliminating the hypothesized distortions.

Parallelism in AI Problem Solving

We have been studying the control issues involved in parallel scheduling in two different AI architectures: blackboard and production systems (OPS5). The work on parallel blackboard systems involves introducing new types of control knowledge for effective scheduling in the parallel asynchronous execution of knowledge sources. This control knowledge is aimed at avoiding excessive conflicts for blackboard access; exploiting the interdependencies among knowledge sources; reordering knowledge source executions to avoid sequential bottlenecking; and not executing knowledge sources if currently executing knowledge sources will invalidate their results. The basis of this knowledge is goal relationships among the different knowledge sources on the agenda. In our work, we exploit several major relationships including inhibits, cancels, constrains, enables, and supergoal/subgoal. We have shown experimentally that the use of specialized control knowledge based on these relationships contributes to more effective utilization of processor resources.

The work on parallel production systems argues that the conventional conflict resolution algorithm is not suitable as a control mechanism for parallel rule-firing systems. Examining all eligible rules within a system imposes a synchronization delay that limits processor utilization. Rather than perform conflict resolution, we propose that rules should be executed asynchronously as soon as they become enabled. However, this approach leaves the problem of controlling the computation unsolved. We have identified three distinct types of control, {it program sequencing, heuristic control}, and {it dynamic scheduling}, which are required for efficient and correct parallel execution of rules. To support these control activities, we have developed an agenda manager that provides support for enforcing consistency of the database, allows the user to specify rule types and groups for sequencing rule executions, and allows both asynchronous and synchronous execution of rules. We are currently adding to the agenda manager the capability to perform dynamic scheduling using meta-level heuristics about rule priorities.

For more detailed discussions of our accomplishments, please see the individual Project Summaries and End-of-the-Fiscal-Year Reports for this contract for each of the five fiscal years 1987 – 1992.

Detailed Summary of Technical Results - October 1, 1990 - September 30, 1991

In this fifth and last year of our URI grant, our focus has been on bringing to maturity important ideas that were developed in previous years. The key research areas that we have focused on are real-time control and planning, sophisticated situation assessment, medium-grain parallelism in AI architectures, natural language processing, and the development of a new methodology for AI research. The last research area was unanticipated in our original research program but grew out of our experience in building a complex real-time problem-solving system (i.e., Phoenix). Other research in the areas of cooperative distributed problem solving, learning, information retrieval, and case-based reasoning, software for building blackboard systems (GBB) that have been important focuses of previous years were given little or no resources during this year and thus are not mentioned. We do, however, list papers published this last year on these areas which represent results of research funded by URI in previous years. The major reason for the elimination of these areas was either the lack of resources (we had a significant decrease in funding) compensated by other sources to continue their support, or the research had reached sufficient maturity that investing further funds seemed unwarranted (e.g., GBB).

Additionally, we have made important progress in exploring the role of parallelism in AI systems. We now have two fully implemented systems on the Symmetry Sequent Multiprocessor. One system involves an asynchronous version of OPS5 and the other a parallel blackboard system. Preliminary results from both systems are encouraging with regard to the application of medium-grain parallelism to AI problem solving.

We have also made important strides in our development of methodology for designing AI systems in a principled way. This methodology bridges what we see as a growing gulf between theoretical and systems-oriented work in AI, but requires a time-consuming rigor that would not be possible without URI support. We have reported new results from research in Phoenix, based on predictive models of Phoenix agent behavior that are verified through empirical analysis. In the second new development, work with this methodology has led to the design of an automated, model-building, researcher's assistant called IGOR that analyzes large data sets and infers causal relationships useful for modeling the underlying phenomena.

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